PhD Thesis

Nuclear processes in intense laser field

PhD Thesis summary

Dániel Péter Kis

BME
Budapest, 2013

Background

Since the creation of the first laser light, there has been a massive progress in the construction of coherent light sources in the last half century. With the increase of intensity of lasers, there has been an ever increasing interest in non-linear optics and non-linear spectroscopy both from theoretical and practical point of view. In the investigations it is assumed that during the matter-field interaction the state of the material remains unchanged. However, if the laser intensity exceeds a critical value ($I_{krit} \geq 5 \cdot 10^{16} \frac{\mathrm{W}}{\mathrm{cm}^2}$) then the electric field strength of the coherent radiation field exceeds the static Coulomb field strength in the H atom at the Bohr radius. At this level of intensity the material loses the atomic structure and partly or entirely goes into plasma state. In this case two process types are typical, which differ in nature: on the one hand there are processes where the collective features of the plasma are prominent (these belong to non-linear optics, for example: self-focusing, induced scattering on plasma oscillation), on the other hand the phenomena are in connection with the individual features of charged particles of the plasma (for example: non-linear Compton scattering, Moller-scattering, etc.)

One of the most important projects of the extreme high intensity lasers' development today is the ELI program initiated by the EU and of which Hungary is one of the main participants [1]. The main goal of this program will is experimental study of the phenomena of laser physics and the field-material interaction in extreme high intensity laser fields. This level of proximity of being able to perform realistic experiments provides actuality for the theoretical study of interaction between laser and material, which already has significant past. It also provides actuality to deepen, expand and further develop the study of the topics. The impact of the appearance of intensive coherent electromagnetic (laser) field on nuclear process is one of these current topics.

From the theoretical study of the interaction of intense electromagnetic field and material it has been deduced that the direct interaction with the nucleus is negligible [2], and the laser can not affect the radioactive decay of the nuclei. Yet, the laser field - through its interaction with atomic electrons

- can cause considerable nuclear effect. Therefore the interest turns to the modification of a special electromagnetic transition of the nucleus-electron system due to the presence of the intense laser field, namely the alteration of the internal conversion process owing to the laser field. In the case of internal conversion process the nucleus gives its excitation energy directly to one of the atomic electrons. With the help of the external electromagnetic field - changing the electron-nucleus interaction process - indirectly the electromagnetic transitions of the nucleus can be changed. Especially those cases are interesting in which the transition energy of the nucleus is smaller than the binding energy of the electron on the given shell, namely when the process is energetically forbidden in the laser free case and the actual transition can become energetically allowed with the absorption of one or more laser photons in the presence of the laser field, i.e. without laser these channels are closed, and they can become allowed in the laser field. Consequently, in theory, the decay constant of the nuclear state can be changed with laser field.

Another interesting topic is the nuclear photo-effect modified by laser which can become experimentally relevant in connection with the extreme intensity laser planned in the ELI. In the nuclear photo-effect a γ-photon gives its whole energy to a bounded nucleon of the nucleus which goes to a free state. As soon as this reaction occurs in laser field, it can be considered to be a special case of the non-linear photo-effect which is similar to the laser assisted x-ray-absorption known from atomic physics. The laser modified nuclear photo-effect is the result of the direct interaction of the laser and the nucleus.

Methods

The aim of my dissertation is to discuss two special physical processes: the internal conversion process in superintense ultrashort laser pulses and the laser-modified proton emission in the nuclear photo-effect. Both processes are developed in the non-resonant case, which means that the energies of the gamma- and the laser-photons and any of their linear-combinations are not equal to any significant energy differences of the process (such as energy differences of electronic and nuclear states). In the calculations I have used the standard non-relativistic time dependent perturbation theory in the semi-classical case, i.e. I have considered the sources as quantum-mechanical objects and I have described the electromagnetic fields as classical fields. In the gauge-invariant nuclear photo-effect the outgoing proton is described by non-relativistic Coulomb-Volkov wave functions.

Theses

1. I have determined the general S-matrix element of the internal conversion (IC) process of a bound-free electron transition applying the modification of electron-nucleus interaction due to a super-intense few-cycle laser pulse. From the S-matrix element I have derived the non-relativistic internal conversion coefficient of an electric transition (EL) in the case of a laser pulse of Gaussian shape. Publications: (A), (B).

2. I have numerically calculated the internal conversion coefficients of originally energetically forbidden internal conversion processes of bound-free electron transitions induced by intense, few-cycle UV laser pulse of Gaussian shape in the case of isomers $^{107\mathrm{m}}$Ag, $^{90\mathrm{m}}$Nb, $^{183\mathrm{m1}}$W, $^{181\mathrm{m2}}$W, $^{188\mathrm{m}}$Re, $^{235\mathrm{m}}$U. Publication: (B).

3. I have investigated the laser parameter (ϕ carrier-envelope phase, τ pulse-length) and energy defect (Δ) dependence of the super-intense few-cycle soft-x-ray laser pulse induced IC process in the case of $^{99\mathrm{m}}$Tc isomer. The results obtained show significant ϕ carrier-envelope phase

dependence of the laser induced IC coefficient. The pulse-effect has its maximum if the phase $\phi = \frac{n\pi}{2}$, in contrast, it has its minimum when $\phi \left(n + \frac{1}{2}\right) \frac{\pi}{2}$. The laser induced IC coefficient drastically increases when the pulse-length is equal to the inverse of the carrier angular frequency ($\tau = \omega_0^{-1}$) and the photon energy ($\hbar c k_0$) of the carrier wave is smaller than the energy-defect (Δ) of the electron-nucleus transition ($\hbar c k_0 < \hbar c \Delta$). The increment is significant compared to the result obtained in the case of plane wave. In the case of $\tau \to \infty$ I have got back the numerical value of the laser induced IC coefficient of $^{99\mathrm{m}}$Tc isomer obtained in the plane wave case [3]. Publication: (A).

4. I have determined the S-matrix element of proton-emission in the nuclear photo-effect assisted by an intense laser field. The calculation is carried out in a gauge invariant manner, in the long wave approximation (LWA) and taking into account the repulsive Coulomb-potential between the outgoing proton and the remained nucleus yet. I have given the gauge invariant differential cross section of the process, while the initial proton is described by Yukawa-type wave-function according to the laser assisted $^8\mathrm{B}\,(\gamma, p)^7\,\mathrm{Be}$ reaction investigated.
   Publications: (C),(D).

5. I have recalculated in gauge invariant manner the cross section of the above mentioned laser assisted $^8\mathrm{B}\,(\gamma, p)^7\,\mathrm{Be}$ reaction and I have compared my results to the numerical results obtained by [4] in this case. The comparison shows that the cross section determined by me is 0.0161 times smaller than the result reported in [4]. The reason for the difference, on the one hand, comes from taking into consideration the Coulomb-correction (about a factor of 1/4) and, on the other hand, the gauge invariant calculation (which results a 0.065 times further decreasing). Furthermore I have determined the partial cross section of nth reaction channel of the laser assisted process in the case of an unpolarized γ-beam and in the case of two different polarization states of the γ-beam. Publication: (D).

6. I have investigated the specificities of the near-threshold laser assisted nuclear photo-effect. The investigations show that the modification caused by the laser field is identical either using Yukawa-type wavefunction or shell-model $\nu s_{1/2}$ state ($\nu = 0, 1, \ldots$) for the description of the initial proton. In other words the R_n (the differential cross section in the nth channel divided by the laser free differential cross section) and the $R = \sum_n R_n$ quantities are independent of the initial proton wave functions mentioned above. It has turned out that the presence of the laser field causes significant modification of the differential cross section compared to the laser free case ($1 \leq R \leq 1.28$). Furthermore R_n is asymmetric to the $n = 0$ value, which results partly due to the Coulomb-correction and to the use of the Coulomb–Volkov states. The numerical results also show that the change of the intensity of the applied laser field significantly affects the angular dependence of the differential cross section in the nth channel. Publication: (C).

References

1 Internet source: http://extreme-light-infrastructure.eu

2 W. Becker, R. R. Schlicher and M.O. Scully, Phys. Lett. A **106**, 441 (1984).

3 P. Kálmán and T. Bükki, Phys. Rev. A **65**, 053414 (2002).

4 A. Dadi and C. Müller, Phys. Rev. C **85**, 064604 (2012).

Publications related to the theses

(A) ***D. Kis***, P. Kálmán, T. Keszthelyi and J. Szívós, *Internal-conversion process in superintense ultrashort x-ray pulses*, Phys. Rev. A **81**, 013421 (2010).

(B) ***D. Kis***, P. Kálmán, and T. Keszthelyi, *Intense few-cycle hard UV-pulse-induced internal conversion processes*, Phys. Rev. A **82**, 025401 (2010).

(C) P. Kálmán, ***D. Kis***, and T. Keszthelyi, *Near threshold laser-modified proton emission in nuclear photoeffect*, Phys. Rev. A **87**, 063415 (2013)

(D) P. Kálmán, ***D. Kis***, and T. Keszthelyi, *Laser-assisted nuclear photoeffect reexamined*, Int. J. Nuclear Energy Science and Technology (2013), megjelenés alatt.

Further Publications

1. P. Kálmán, T. Keszthelyi, and ***D. Kis***, Eur. Phys. J. Appl. Phys. **44**, 297-302 (2008)

2. P. Kálmán, T. Keszthelyi, and ***D. Kis***, Eur. Phys. J. Appl. Phys. **50**, 31101 (2010)